Renewable and Sustainable Energy Reviews 16 (2012) 5087–5100

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy management in horticultural applications through the closed greenhouse concept, state of the art

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ARTICLE INFO

Article history:
Received 18 April 2011
Received in revised form
17 April 2012
Accepted 18 April 2012
Available online 27 June 2012

Keywords:
Sustainable energy management
Closed greenhouse
Thermal energy storage
System modeling
Energy analysis

ABSTRACT

The commercial greenhouse has the highest demand for energy as compared to all other agricultural industry sectors. Here, energy management is important from a broad sustainability perspective. This paper presents the state-of-the-art regarding one energy management concept; the closed greenhouse integrated with thermal energy storage (TES) technology. This concept is an innovation for sustainable energy management since it is designed to maximize the utilization of solar energy through seasonal storage. In a fully closed greenhouse, there is no ventilation which means that excess sensible and latent heat must be removed. Then, this heat can be stored using seasonal and/or daily TES technology, and used later in order to satisfy the heating demand of the greenhouse. This assessment shows that closed greenhouse can, in addition to satisfying its own heating demand, also supply the demand for neighboring buildings. Several energy potential studies show that summer excess heat of almost three times the annual heating demand of the greenhouse. However, many studies propose the use of some auxiliary system for peak load. Also, the assessment clearly point out that a combination of seasonal and short-term TES must be further explored to make use of the full potential. Although higher amount of solar energy can be harvested in a fully closed greenhouse, in reality a semi-closed greenhouse concept may be more applicable. There, a large part of the available excess heat will be stored, but the benefits of an integrated forced-ventilation system are introduced in order to use fresh air as a rapid response for primarily humidity control. The main conclusion from this review is that aspects like energy efficiency, environmental benefits and economics must be further examined since this is seldom presented in the literature. Also, a variety of energy management scenarios may be employed depending on the most prioritized aspect.

Contents

1. Introduction

Sustainable energy management is one of the most important topics of research with global benefit. Here, energy consumption, environmental impact and cost efficiency are central aspects for achieving successful sustainable energy management scenarios. Sustainable horticulture[1] is one challenging task since the

[1] "Practice of growing plants in a relatively intensive manner" [Principle of horticulture, C.R. Adams, M.P. Early, Elsevier butterworth-Heinemana, ISBN: 0750660880].

Abbreviations: ACCFHES, Aquifer Couple Cavity Flow Heat Exchanger System; AHU, Air Handling Unit; ATES, Aquifer Thermal Energy Storage; CFD, Computational Fluid Dynamic; CHP, Combined Heat and Power; FiWihex, Fine Wire Heat Exchanger; HME, Heat and Moisture Exchanger; LMTD, Log Mean Temperature Difference; PCM, Phase Change Material; TES, Thermal Energy Storage

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http://dx.doi.org/10.1016/j.rser.2012.04.022

world-wide increase in population leads to a need for higher production yield in agriculture, which in turn leads to a rise in the energy demand of the agricultural industry. The average of European Union countries energy demand in the agricultural industry is 1.8 {MWh/ha-year} and in the Nordic countries, e.g. Sweden, it is higher at 3{MWh/ha-Year} [1]. Although it is small as compared to the total energy demand in many countries, it is significant in some countries such as the Netherlands where it represents almost 8% of total energy use in the agricultural industry [1]. One of the most energy consuming sectors in the agricultural industry is the greenhouse. The greenhouse has been implemented for centuries in order to increase yield and control growth in all climates. Analyses of the greenhouse technology started in the 1950s, with an increase in the late 1970s when many studies sought improvements in commercial greenhouses due to the oil crises [2,3]. In recent decades, the innovation idea of using closed greenhouse was formed in order to conserve water and energy [4]. A horticulture closed greenhouse can be used as a source of energy as well as for agricultural purpose. This should be considered e.g. in lieu of the statement by Hare et al. who declared that 70% of greenhouses are heated with a supplementary unit of which 90% of them use oil as fuel [5]. However, for Nordic conditions the oil consumption has recently been reduced by 50% while the use of the other energy sources such as biomass has increased 18% between 2005 and 2008 [6]. Fig. 1 presents the different energy sources used in the greenhouse sector in Sweden. From this graph it can be concluded that presently the overall policy in the horticultural industry regarding the energy consumption is to reduce fossil fuels and replace them with other renewable sources.

As compared to conventional greenhouse technology, the closed greenhouse can in principle be independent of fossil fuel since it is designed to maximize the use of solar energy through seasonal thermal energy storage (TES). Using the concept, the greenhouse also becomes independent of the weather situation and can then in principal be used all over the world. However, limiting conditions depend on the geology of the ground since underground seasonal storage is presently the only cost-effective option, the type of heating and ventilation system implemented inside the greenhouse, and the rate of solar radiation. In the predominately hot and arid region it should still be possible to use a closed greenhouse although the water temperature in the storage system must be maintained low enough for cooling. Although closed greenhouses may require a higher capital investment as compared to conventional greenhouses, there is still a possibility to cost-effectively implement the concept [7]. Cost competitiveness of closed greenhouses is dependent on size, as well as the type of TES used and other installations. This paper presents a state-of-the-art assessment of the closed greenhouse concept, with the objective of setting the stage for further advancement of this very promising concept for energy management and sustainability. Specifically, advantages and challenges of the closed greenhouse concept in comparison with conventional open greenhouse concept are discussed. In addition, appropriate climate control strategies and technologies for the closed greenhouse concept are described, with special attention given to various types of TES systems to be implemented. Finally, this information is used to discuss the energy management potential through the closed greenhouse concept.

2. The closed greenhouse concept

Since the closed greenhouse concept is not a widely implemented concept there is no specific definition available in the literature. However, one reference described it as follows:

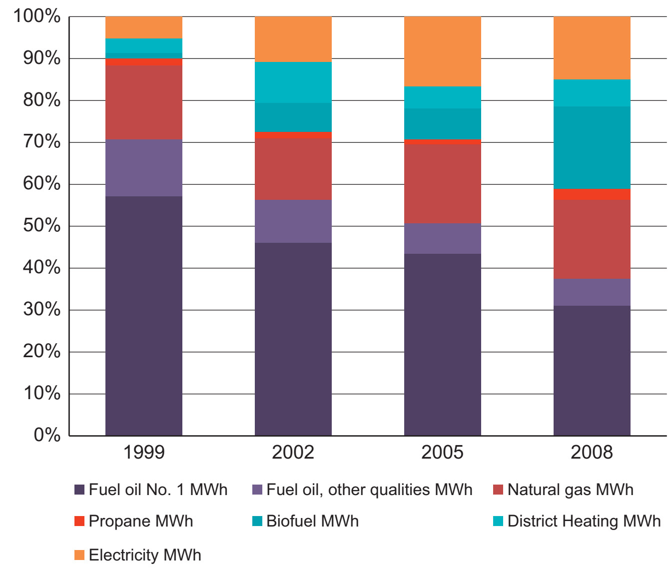

Fig. 1. Portion of the energy sources which has been utilized in the horticultural industry between 1999 to 2008 [6].

> "A greenhouse, which is completely closed, no windows to open to release excess humidity or to cool the house when it is too warm" [4].

As previously mentioned, provided that TES is effectively integrated, the closed greenhouse can be independent of fossil fuel and weather. The closed greenhouse can supply heat for itself and other nearby buildings. However, in practice an auxiliary system may be employed to supply part of the peak energy demand. If this system is based on biomass, then all of the supplied energy is of renewable origin. The greenhouse can be considered as a large solar collector. It can collect around 80% of the incident solar irradiation which is around 2.5 GJ/m^2-year for north of Europe [8]. Solar energy is transformed into heat inside the greenhouse. Since this amount of heat is more than required in hot and sunny days, it should be captured and stored in a TES system for re-use whenever the greenhouse needs to be heated. One concept proposed is underground thermal storage systems [9]. For example, the aquifer storage can be integrated with a heat pump system for heating and cooling a closed greenhouse.

In a simple design, which is presented schematically in Fig. 2, the heating and cooling processes rely on storage TES system, heat pump and heat exchanger. In the heating mode (Fig. 2a) the greenhouse will be heated using a heat pump. Warm water is then extracted from the TES and delivers low temperature heat to the heat pump while being cooled. Then, the cooled water is returned to the TES-system and thus charges the cold side of the TES. The heat pump provides the hot water. The hot water will charge a short-term buffer storage which is used to level the daily/hourly load in the closed greenhouse. In the cooling mode (Fig. 2b), cold water from the cold TES is pumped directly into the greenhouse and removes heat via a heat exchanger system. Then, the warm water is brought to the warm TES charging it for the winter. There are many other options for managing the heating/cooling demand and they will be described in the following sections.

2.1. Advantages and applications

Agricultural technology is faced with three important aspects: energy consumption, environmental impact, and economical constraints [2,7,10–12]. All these aspects should be considered

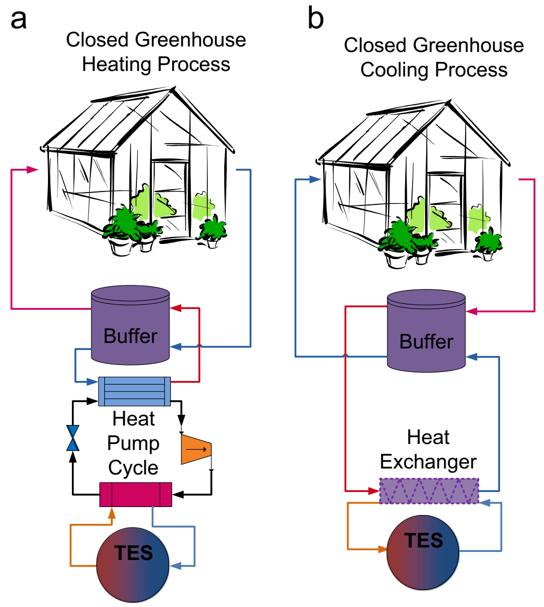

Fig. 2. Conceptual FEATures of a closed greenhouse: (a) heating mode and (b) cooling mode.

to have an efficient system with regards to sustainable development in agriculture. With the increase in population, as well as the increased development of new production technology, the energy consumption of the agricultural industry may increase. Although the greenhouse is one of the most energy consuming sectors in the agricultural industry, it is important because of the ability to intensify production [4]. In order to improve the energy conservation in greenhouses the idea of using closed greenhouse was formed [4,13,14].

The main advantages of closed greenhouse as presented in the literature are [4,7,10,13–18]:

- Improved energy efficiency.
- Improved water conservation.
- Improved production rate.
- Improved control of system.
- Improved total efficiency of system.
- Improved sustainable management.
- Decreased usage of pesticides.
- Reduced costs.
- Increased use of renewable energy which leads to reduced greenhouse gas emission from fossil fuels.

The cost benefit of the closed greenhouse concept depends on many parameters such as primary energy cost and total production yield, with the increased yield being the most important [19]. Therefore, although the closed greenhouse concept may have high investment cost, it still can be cost effective due to the higher yield as well as lower energy cost. It has been indicated that the closed greenhouse concept has the potential to increase production yield up to 20% while the total primary energy demand will reduced by 30–40% [20]. Paksoy [21] compared a conventional and closed greenhouse on a number of parameters for Turkish conditions. This comparison showed that with 25% higher annual capital cost, the fruit yield increased with nearly 40% and annual cost of energy was only 1/3 of that of the conventional greenhouse.

From the assessment of published work, it is evident that the closed greenhouse concept is a rather new idea. Heuvelink and Bakker state that the first closed greenhouse was built in 2002 in the Netherlands and is called "Themato" [19], which was a pilot-sized project. Then, the first commercial scale closed greenhouse was developed by the same company under the name: "GeslotenKas" in 2004 [20–22]. The GeslotenKas greenhouse is designed as a "Partly closed greenhouse" which means that the surplus in heat energy from the closed greenhouse portion is used also for heating the conventional greenhouse portion. Here, it should be noted that the "partly closed greenhouse" is different from "semi-closed greenhouse" in that the partly closed concept consists of a closed and a conventional area with the energy demand for the conventional part being supplied by the closed portion. The semi-closed greenhouse is an "almost" closed greenhouse where part of the cooling demand will be supplied by open ventilation windows.

TES systems are essential in the closed greenhouse concept as they give the possibility of storing excess energy for reuse whenever it is needed. Therefore, it can eliminate the mismatch in energy demand and energy supply for many conditions. As an extension of the concept, a closed greenhouse together with a supplemental co-generation system, water treatment, and waste management systems can be a sustainable solution in an urban area as well as in horticulture. This idea, in the literature named "the greenhouse village" [9,10] is an initiative for sustainable technology development. Here, the closed greenhouse captures the solar energy using for example an aquifer as TES. This system is then integrated with a secondary energy conversion unit like a biogas plant coupled to a combined heat and power unit (CHP). Cooling, heating and electricity of the greenhouse and also the surrounding buildings can then be supplied by the "greenhouse village".

The closed greenhouses need only low volumes of external water which can in many cases, be supplied by rain water [1]. Thus, another advantage is water conservation. Waste water as well as plant wastes can be treated and reused for this purpose. If the humidity becomes higher than a certain limit, a dehumidification system must reduce the moisture content. From data published in the literature, it is shown that the closed greenhouse concept will reduce water consumption for the irrigation by 50–80% [20,23–26]. There are many R&D-projects on the closed greenhouse concept in countries such as Netherlands, Canada, Finland and Turkey. Here a short description of the three most recent Dutch projects are given, with information on additional projects summarized in Table 1. One program, called "greenhouse as energy source", has been launched in the Netherlands [22]. It aims at reducing CO_2 emission about 50% due to the much lower fossil fuel consumption. Presently, three closed and semi-closed greenhouse prototypes are built under this program. They are: "Sunergy Greenhouse", "Sun Wind Greenhouse" and "Flow-Deck Greenhouse" [27].

Sunergy is a semi-closed greenhouse with the main innovation being with regards to radiation issues [27,28]. In this greenhouse a glass with a special coating is used in order to transmit more radiation than ordinary greenhouse glass. A double screen is used in this greenhouse in order to minimize the heat loss due to sky radiation especially at night. Since uniform temperature distribution reduces the heating and cooling consumption an overhead cooling unit is implemented in this greenhouse. In the Sunergy greenhouse, outside air is utilized for dehumidification purpose during nights and overcast days in order to reduce the investment costs [28].

For the Sun Wind greenhouse, the main innovation is the use of solar collector strips as the greenhouse shading screen. Using double glazing at 35° slope with adjustable panel, solar energy can be stored in form of hot water and prevents direct sunlight from entering the greenhouse [27]. This greenhouse is integrated with a wind turbine to provide electricity for the greenhouse, and any excess electricity generated can be delivered to the power grid.

Table 1
An overall review on different closed greenhouse issued scientific reports.

Name of greenhouse/ Project		Aircokas	Zero fossil energy greenhouse	Themato	ECOFYS	Energy producing greenhouse	Watergy	GESKAS PSKW &PCH	ENEA
Type		Semi-closed	Semi closed	Closed	Partly-closed	Partly-closed	Closed	Closed	Closed
Area		700 ha	1 ha	1,4 ha	1400 m2	1 ha	1 ha	160 & 240 m2	9000 ha
Thermal management systems	Auxiliary heating source	Heat pump	CHP; boiler; heat pump;	CHP; heat pump; AHU	Boiler; CHP; heat PUMP	Natural gas; geothermal; heat pump	Nothing has been specified	Co-Generation; boiler; heating coil;AHU	Boiler; heater; AHU
	Cooling source	Active cooling	Active cooling	AHU; active cooling	Absorption; chiller; free cooling	Active cooling; free cooling;	Natural convention established by a tower; Shading	Cooling coil; AHU	Active cooling; AHU
	Energy storage system	ATES; buffer	ATES; buffer	ATES; buffer	ATES; buffer	ATES; buffer	Nothing has been specified	ATES; buffer	Battery storage
Advantages		30–45% CO_2 emission reduced	2% higher production	17% higher production&30% fossil fuel reduction	50% energy efficiency improvement;20% more Production; 50% less water consumption	12% higher production	75% reduction in water consumption	6% higher production; 34% less primary energy consumption	Cut down mainly cost for electricity demand for forced ventilation and active cooling
Economical Issues		Investment cost can be covered by 20% extra production	10% higher cost compared with conventional greenhouse	Cost competitive due to higher total yield		The total benefit depends on energy demand, energy price, energy saving, production, closed part fraction	Minimum electrical power cost		
Experimental/Simulation result		Experimental results				Simulation results			
Reference		[75]	[11]	[19]	[20]	[74]	[26]	[22]	[76]

Finally, the "FlowDeck" greenhouse is the most recently developed greenhouse. Here, the main innovative characteristic is using a hollow core sheeting in which water flows. Thus, the insulation of the greenhouse is improved during cold periods, and excess heat is removed during warm period via the water circulating in the core [27]. The main challenge in this greenhouse is the reduction in transmissivity of irradiation due to the water in the core. In all these three greenhouse concepts, a TES system should be coupled with the greenhouse in order to provide the heating and cooling demand all year around. In addition to these concepts, many researchers are investigating strategies for closed greenhouse and their technical and economical advantages. Table 1 presents an overall review on scientific reports on closed greenhouses found in the literature.

In summary, this assessment shows that closed greenhouse can be feasible and cost competitive in comparison to a conventional greenhouse due to higher production. Furthermore, it is evident that the auxiliary heating systems are essential in order to have a reliable thermal management system. This auxiliary system can be a heat pump to raise the temperature of the water from the warm aquifer, as well as auxiliary heaters. As shown in Table 1, a variety of available technology for heating and cooling are proposed, but no optimized method of selecting system layout has been found.

2.2. Closed greenhouse indoor climate

The possibility of controlling all climatic parameters in the greenhouse is the main point of interest in the cultivation industry. In order to have optimal growing conditions, the greenhouse climate should be kept close to the optimal temperature during all cropping periods [3,13,29]. It also has a considerable impact on the energy conservation in the greenhouse where a decrease of one degree set point temperature causes about 10% decrease in greenhouse energy demand [3]. According to another study by Dieleman, a reduction in the daily average greenhouse set-point temperature leads to 16% decrease in the annual energy demand however the annual production yield decreased by 3% [13]. Here, the optimal temperature is different for different crops and even for different periods of growing of a specific plant. In a conventional greenhouse, temperature control is obtained through ventilation/heating and is thus affected by the surrounding climate fluctuation [29]. In the closed greenhouse this is not the case and the greenhouse can operate more independently of the surrounding climate [9]. Nevertheless there are other challenging points in a closed greenhouse when it comes to cooling and dehumidification [5,12,19,25]. High humidity in combination with lower irradiation level in winter is dangerous for the plant as well as low humidity in combination with high irradiation level [30]. The high humidity will lead to scarce uptake and transport of nutrients and consequently a lower plant quality. Too low humidity (relative humidity below 65% [31]) and high radiation amplifies the transpiration more than the plants can handle and the plant start wilting [23]. It is believed in general that the ideal relative humidity for plants growth is around 80–85% [32]. Here, a short review on the heating and cooling systems, as well as the challenges with the respective solutions, are described in the context of closed greenhouse application. The aim is to aid the

design of feasible systems to be utilized in the closed greenhouse. Although the closed greenhouse concept is an innovative idea, heating and cooling options is based on the commercial greenhouse thermal devices.

There are many parameters that should be considered in the design of a greenhouse heating system, here divided into three subjects [3,13,18,24,28]:

- Obtaining uniformly distributed temperature gradient in the greenhouse in order to have uniform growing and avoid local condensation.
- Keeping the leaf temperature above the dew point to avoid condensation on the plant.
- Lowering the energy demand as much as possible.

Geiling et al. [18] monitored the climate variables in the closed greenhouse and observed that the temperature gradient in the closed (semi-closed) greenhouses is larger in comparison to the conventional greenhouses.

One of the most promising methods for lowering the energy demand in the greenhouse is the use of double glazing instead of single glazing. A 45% decreasing in the energy saving has been reported [3]. However, depending on the material, the solar transmission in the double glazing may be up to 20% less than for single glazing which then reduces the yield and crop quality [3]. Therefore an artificial light should be used or the glazing material needs to be improved (e.g with anti reflective coating) in order to have a higher light intensity inside the greenhouse [3]. In addition the temperature inside the double glazed greenhouse is higher than the single glazed greenhouse which may lead to a higher dew point and reduces the evapotranspiration in the crops. Therefore by using the double glazed greenhouse the risk of fungi infection can be increased [3].

Baille et.al state five different heating systems that can be used alone or in a combination for the greenhouse application [33]:

- Heat exchanger buried in the plant soil.
- Heat exchanger laid on the ground.
- Hot water pipe network near the ground.
- Fan-coil heater units.
- Roof pipe heating system.

The location of the heat exchanger can affect the microclimate control in the greenhouse. In order to facilitate the climate control it has been recommended to locate the heat exchangers close to the crops and near the soil [34]. This also leads to more uniform gradient temperature regarding to the air and leave [35]. In another presentation, heating systems which are applied in the greenhouses was categorized in two main types: pipe or air heating method [15]. Many studies have investigated the different aspects of these two types of heating systems. Teitel et.al [24] showed that there is no considerable difference between pipe and air heating system with regards to energy consumption. The same study also showed that with the pipe heating system, the crops which are facing to the pipe are considerably warmer than the surrounding air. With the air heating system the plants are generally cooler than the surrounding air and this increases the possibility of fungal diseases due to high possibility of condensation on the leaves [24]. Van de Braak et al., have compared pipe and air heating with each other and as a conclusion claim the main benefit of the air heating system is its quick response to the control [35,36]. However, the electricity consumption is higher than for pipe heating system with increasing temperature, the humidity ratio at crop level also increases [24]. However, Hoare et.al have shown in their paper that the rate of increase in humidity ratio with the air heating system is larger than with the pipe heating system. In fact, in the pipe heating system the humidity ratio will be almost steady in compare with air heating system [37].

Commercial cooling systems in the greenhouses can be divided in three main groups: ventilation system, shading (reflecting) and evaporative cooling. The greenhouse can be ventilated by natural ventilation or by forced ventilation but the efficiency of ventilation cooling highly depends on the outdoor climate [15]. Natural ventilation systems have not been further considered in this report since closed greenhouses do not have any ventilation windows. However, the forced ventilation system may be used in order to prepare uniform indoor temperature and adjust humidity, then forming the semi-closed greenhouse. In the Sunergy greenhouse, which is a semi-closed greenhouse, the humidity can be adjusted with a controllable flow rate of 5 to 15 m^3/m^2 per hour [28]. Shading or reflecting (thermal screen) reduces the total heat gain by covering the glass and reduces the solar irradiation through the greenhouse [30]. A 80% decrease in the greenhouse energy demand has been reported with a combination of three layer of thermal screen [3]. Although this method can be used very efficiently to decrease the greenhouse temperature based on Cohen's results [37], it is not appropriate in a closed greenhouse since it blocks the solar radiation energy instead of capturing it with solar thermal storage system. Shading with the solar collector plate can be an innovation to solve this problem as proposed by Wageningen UR [27]. Sethi et.al surveyed a variety of greenhouse cooling systems, of which three common types of evaporative cooling are [38]:

- Fan-Pad system.
- Fog system.
- Roof evaporative cooling system.

The principle of the fan-pad system is based on passing air through a wet pad by mechanical force [39]. The fog system is making cool air by spraying small droplets of water with high pressure into the air. With this method the contact surface of water will be increased and then the heat transfer ratio can be increased as well [40]. The roof evaporating cooling system is similar to the fog system but the only difference is that in this system water will be sprinkling on a surface of the roof. With this system a thin film of water can be formed to increase the evaporation rate [38]. Arbel et.al made a comparison between fog system and fan-pad system, and concluded that the fog system has better performance in comparison with fan-pad system [41]. The disadvantages of the fan-pad system are [38]:

- Un-uniformity of the temperature distribution.
- Considerable resistance to the air passage since the air have to be forced through the pad.
- Expensive installation, operation and maintenance cost.
- Clogging of the pad.

Tables 2 and 3 summarize greenhouse heating and cooling technologies, respectively. The focus is mainly on the heating or cooling power and the operational conditions of the systems.

In the second column of each table a classification is made: direct or indirect. This is with regards to if the greenhouse air is directly conditioned in a separate place and then is distributed inside the greenhouse (direct), or if an external media like hot water exchanges heat with air through a fan coil unit for instance (indirect). For indirect technologies an additional heat exchanger is always needed.

For this purpose, the FiWihex technology, which stands for Fine Wire Heat Exchanger, is an efficient heat exchanger capable of transferring a large amount of heat from water to air (heating) or from air to water (cooling) while the temperature difference is

Table 2
Heating technology and devices.

Device	Category	Heating power [kW]	Operating temperature	Other issues
FiWiHEX [42]	Indirect	0.9–1.2	ΔT for aquifer water (supply–return) =8 °C	Heat delivery from the aquifer, COP: 8–11
Ground air collector (GAC) [77]	Direct	11–33 [kWh][a]	ΔT=0°C to 12 °C (difference between suction and delivery for air)	Air flow: 100 kg/hr
Air heat exchanger (EAHE) [77]	Direct	6–28 [kWh][b]	0°C to 9 °C (difference between suction and delivery for air)	Air flow: 100 kg/hr
Ground storage heat pump (GSHP) [78]	Indirect	10.5	Temp. change of working fluid: 6 °C	Water flow rate:30 l/min
Fan coil unit [79]	Indirect	0.5–11	ΔT water in fan coil: 15 °C to 20 °C	Air flow : 2408 kg/hr (mean), Conditions: T=20 °C, RH=50%
Gas heater blower [79]	Direct	7–94	Max air temperature rise 38 °C	Works by natural gas or propane as fuel, need a ventilation pipe, air flow through blower: 5440 CFM max
Electrical unit heater [79]	Direct	5–50	Max air temperature rise: 39 °C	Air flow rate: 3575 kg/hr
Infrared heater [79]	Direct	1.5–12	N/A	All data available, heat density in W/m^2 is available
Hot water fan coil heater [79]	Indirect	3.5–80	ΔT of the air: 18 °C to 33 °C	Air flow rate: 470–587000 kg/hr
Steam fan coil heater [79]	Indirect	5–100	ΔT of the air: 26 °C to 44 °C	Air flow rate: 470–587000 kg/hr

[a] Heating capacity has been reported instead of the power of GAC due to the reference.
[b] Heating capacity has been reported instead of the power of EAHE due to the reference.

Table 3
Cooling technologies and devices.

Device	Category	Cooling power [kW]	Operating temperature	Other issues
FiWiHEX [42]	Indirect	1.5–1.9	Power is per 1 °C temperature difference between air and water	N/A
Ground storage heat pump (GSHP) [78]	Direct	10.5	Water from aquifer extracted at 14 °C	Water flow rate: 177 l/min
Fan coil unit [79]	Indirect	8–9	ΔT of the water circulating in the coil: 6 °C	Air flow : 2360 kg/hr,Conditions:T=25 °C, RH=50%
Evaporative pad system [79]	Direct	25–220	ΔT of the air: 10 °C–15 °C	Complete PVC or Aluminum
Fog system cooler [79]	Direct	5–110	Air temperature reduction: 8–20 °C	N/A
Vapor compression chiller [79]	Direct	8–56	ΔT evaporator side=6 °C ΔT condenser side=5 °C	N/A

very low. Thus, FiWihex is a type of fan coil unit and can then be integrated with the TES system so that in the summer the greenhouse area is cooled and heat is stored, and in the winter the low grade heat from the TES is transferred to the greenhouse area through FiWihex while the temperature difference is not high [42,43]. This kind of highly efficient heat exchanger is advantageous for closed greenhouses since heat exchangers have to operate with low temperature difference in closed greenhouses [42,43]. The Fiwihex heat exchanger promises to decrease level of noise in the greenhouse caused by air movement systems beside low disturbance of the crop [42]. This technology is in use in the Netherlands in a 2500 m^2 greenhouse since 2005 [9].

Humidification in closed greenhouse will be similar to in an open greenhouse, i.e. a combination of heating and adding water vapor to the space (e.g., a fog system). As opposed to the previously mentioned categorization, Shelly et.al categorized humidification methods in three different types of humidifiers [44]:

- Cold water humidifiers.
- Hot water humidifiers.
- Nebulizers.

In the cold water humidifiers the air passes over the water in the water reservoir, or it passes through the water. In this case the temperature can be constant or the change is negligible. The cold water humidifier principle is simple and it is inexpensive. On the other hand, microbiological colonization may occur in the reservoir which can affect the air quality. Air leakage from the reservoir is unavoidable in this method [45]. The hot water humidifiers principle is the same as cold water humidifiers except this fact that the hot water humidifier are using a heater to make saturated vapor at the outlet [46]. In the nebulizers instead of water vapor, supersaturated mist of water droplet will be produced. In this method an aerosol of water droplets is produced by a plate which is oscillating at ultrasonic frequency [44]. Table 4 compares various methods for humidification [47–50].

The main challenge in the closed greenhouse indoor climate control is with regards to dehumidification since the ventilation cannot be used in the fully closed greenhouse concept [29]. However in the semi-closed greenhouse ventilation can be considered as one alternative for dehumidification system. In a very basic categorizing dehumidification can be divided into two methods: refrigeration and desiccant [51,52]. Refrigeration-based systems remove moisture in a condensation mechanism by using coils to cool the air to a saturation condition and sometimes later reheat it after enough moisture has been removed. Therefore, the dehumidification and cooling can be done at the same time in most cases. Harriman et al. has

Table 4
Comparison between different types of humidifiers [47–50].

	Cold water humidifier	Hot water humidifier	Nebulizer	Heat-moisture exchanger
Temperature	18–23	36–38	23–36	No data
Absolute humidity (mg/lit air)	15–20	42–47	177–1536	27–36
Temperature stabilization	No data	Good	Cause local cooling	Good
Problem	Air Leakage, microbiological colonization	Inaccurate controlling, electrical malfunction, installation and maintenance, bacterial colonization.	Has electrical risks, expensive	Increasing in airway resistance, cannot be combined with other type of humidifier
Commercial	High	Moderate	Low	High
Cost	Moderate	High	High	low

compared four types of cooling based dehumidification systems, as summarized in Table 5 [52]. In contrast, sorption (desiccant) systems directly extract moisture from the air in a vapor phase; this occurs without a cooling effect and produces air with a higher temperature due to heat of adsorption and this lead to lower humidity content [53]. The humidity can be controlled with any kind of sorption technology independently from temperature controlling. A sorption system dehumidifies the air using desiccant substances instead of using coils, and thus freezing the coils in the low temperature and humidity condition can be avoided [51]. It should be noted that the desiccant must be regenerated in order to release the absorbed moisture. The desiccant can be regenerated with hot air which is called reactivation air. In the closed greenhouse village concept, the reactivation air can be supplied by a heat recovery system integrated with heat pump or thermal energy storage. However, it can also be supplied directly by solar air heater. A combination of desiccant and refrigeration-based dehumidification system has the potential to be the most efficient method for many applications because the limitation of each method will be compensated by the other advantages [54]. The other advantages of the desiccant dehumidification are given below [52]:

- Cost and energy efficient.
- No wet coils cleaning required.
- Avoid microbiological and fungal colonization since duct system is dry.
- Low grade heat can be utilized.
- Operate in the low dew temperature that is below practical limits of cooling dehumidification systems.
- Small size and easy installation and maintenance.

Other benefits of using this system are mentioned as lower operation cost and lower peak electric demand [54]. It is possible to switch latent cooling to alternate energy source such as natural gas, steam or heat recovery. The heat recovery alternatives , which can be used integrated to this system, are [55]:

- Heat driven chillers.
- Cogeneration.
- Condenser heat.
- Steam condensate.

A comparison between methods for refrigerative and desiccant based dehumidification is summarized into Table 5 [55]. However, the particular usefulness of desiccant systems in closed greenhouse applications can only be assessed through an annual performance analysis considering heating and cooling (sensible and latent) in combine.

Regardless of the dehumidification method the energy used in the dehumidification process can be lowered using the following three methods [13]:

1. Increasing the humidity set point: based on a report in the literature, a 4% decrease in annual energy demand has been reported for a 5% increase in the humidity set-point [56].
2. Reducing the transpiration by removing the leaves of the crops. A study by Adams et al. shows a 30% decrease in annual energy demand by removing the old leaves [57].
3. Dehumidification with heat recovery in the semi-closed greenhouses [13].

2.3. Theoretical models for energy analysis of greenhouses

One important tool to further advance the concept of closed greenhouse for energy efficiency is proper modeling, in order to assess the technical potential of a variety of design concepts as well as the cost-effectiveness. Mass and energy balance are the basic conceptual equations which are used to model the various processes in any thermal system, the greenhouse being no exception. For this case, the energy and mass balances state that the amount of energy stored will be equal to the sum of the energy which is gained by internal energy sources, and the solar irradiation gains, minus the losses. These losses are due to conduction through the cover, long and short wave radiation, evaporation regarding to the ventilation, heat exchanger and infiltration. This is conceptually outlined in Fig. 3. With regards to the water mass balance, the rate of change of humidity will be the sum of changes due to ventilation and infiltration; the humidification/dehumidification; and the difference between evaporation and condensation. Several theoretical models for mass and energy flow analysis of a greenhouse have been previously presented. Table 6 summarizes the different characteristics of these models. All of them contain assumptions and simplifications to varying extent. However, they can still be used to estimate desired variables such that indoor temperature and humidity. Although simplification is necessary to have an applicable model, there are parameters that must be considered to have a complete model. For a greenhouse model these are for example: plant carbon balance, photosynthesis, respiration, and allometry [58]. Allometry is the study and measurement of the growth rate of plants. The model should be as general as possible to apply to many situations possible in an open and closed greenhouse. However, it should at the same time be complex enough to satisfy all required details.

Table 6 is a summary of five different methods for modeling the greenhouse. The first model [59] is a very general model

Table 5
Overall comparison between different types of desiccant dehumidification system [38,53–55].

Desiccant dehumidifier		
Liquid spray tower	*Advantages*	Large air flow capacity Provides microbiological decontamination Reduced regeneration air requirement Energy storage capability Easy maintenance Low amount of leakage. Air temperature and humidity are controlled separately but simultaneously
	Disadvantages	Difficult to maintain humidity level below 10% RH with load which have small sensible component.
Solid packed tower	*Advantages*	Have the capability to reach a very low dew point
	Disadvantages	High dependency of performance on air velocity
Rotating horizontal bed	*Advantages*	Output condition is independent on level of moisture trapped Well adaptive with high flow rate Low initial cost Simple design
	Disadvantages	Possibility of air leakage Desiccant substance settling in trays
Multiple vertical bed	*Advantages*	Output condition is independent on level of moisture trapped High performance Low dew point
	Disadvantages	Complex design More maintenance required Higher initial cost
Rotating desiccant wheel	*Advantages*	Light weight Low pressure drop Low dew points High capacity Simple design
	Disadvantages	High initial cost
Refrigerative dehumidifier		
Dual path system	*Advantages*	Low operating cost Direct control of ventilating quality Good humidity control Small size system
	Disadvantages	Additional maintenance is needed Not applicable for heat storing
Heat pipe system	*Advantages*	Higher performance in comparison to a system without heat pipes Energy saving Simplicity
	Disadvantages	No considerable weakness
Run around coil system	*Advantages*	Reduces the cooling load on the main cooling coil Less extra energy consumption for reheating and re overcooling
	Disadvantages	Costly Require extra maintenance
Conventional cooling system with reheat	*Advantages*	Simple configuration Good humidity control Low initial cost
	Disadvantages	Need more reheat in lower load condition thus more annual energy consumption Energy wasted in overcooling and reheating supply air

for an open greenhouse considering a four homogenous layer control volume in the greenhouse model: cover, air, crop and the soil as shown in Fig. 4. The results from the simulation based on this model were verified by experimental results. There was good agreement between these two types of results, therefore this model can be used as a basic model to investigate the effects of other parameters on the greenhouse microclimate performance [59].

The second model [60] is based on a well isolated greenhouse and it can be used as a model for closed greenhouse as well. It was originally derived to assess the effect of evaporative cooling at different conditions in the greenhouse, but its results were not validated with experimental results. However, the results were found comparable to other previous results which were developed by other researchers [60]. The third model [61], considers closed greenhouse integrated with a PCM storage system. Here, results are said to be validated experimentally by the authors although it must be questioned if it is really appropriate to ignore the latent heat effects of water vapor and evapotranspiration as was done in this case.

The fourth model [58] by Hill, is a modified model based on Monteith model [62]. This model is one of the most complete models which is given for the greenhouse energy and mass balance. It suggests assuming lumped parameter method for modeling a greenhouse. In a lumped parameter method spatial variations are ignored and all internal fluxes through the control volume's boundary are assumed to have uniformed distribution [58]. However, this model is a simplified model of the tree seedling nursery regarding to energy management. Therefore it should be modified for typical commercial greenhouses.

Finally, the fifth model [63] is a thermal model of the greenhouse based on one special type of indoor climate system: an aquifer coupled cavity flow heat exchanger system (ACCFHES). This model is simple, friendly to the user, and convenient to apply in any other type of greenhouse by employing different initial values and boundary conditions. ACCFHES is analyzed by LMTD method. The results are verified for a special case study but there is no general validation for this model. There are many parameters and constants that are used for the validation but they are based on experimental data from the specific greenhouse under study in that case.

Based on analytical equations many former researchers have developed their own computerized models in order to analyze the energy consumption in a greenhouse. Some of the most recent models are described here and will be compared [19,22,64–71]. Table 7 presents the summarized comparison between these models. Fuller, Hollmuller and Hoes developed their models based on the TRNSYS simulation program [72]. In their models a new type is defined through TRNSYS which is called "greenhouse". This type is mostly based on a pre-defined building subroutine in the TRNSYS standard library. Its components are validated partially in different greenhouses. This model is more

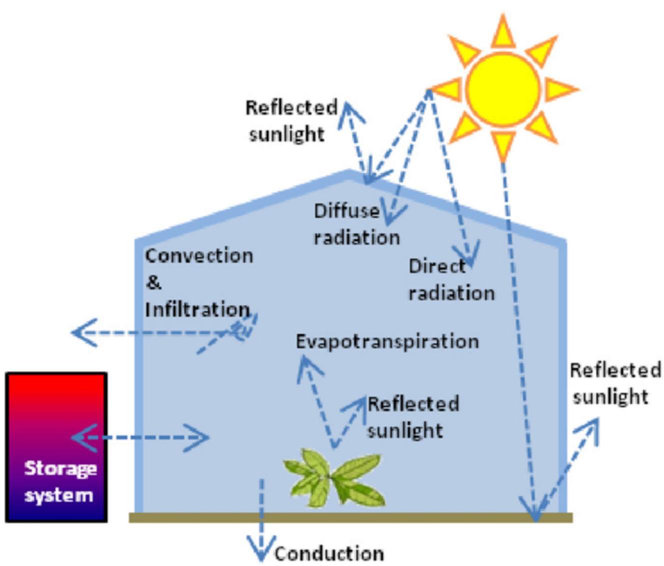

Fig. 3. Heat transfer model in the closed greenhouse concept.

concentrated on the heat exchangers which are employed in the greenhouse [17,64,66]. Hoes compared two closed greenhouse models with each other and also with conventional condition according to the GESKAS project. In GESKAS, two closed greenhouse models, PSKW and PCH, are included [22]. In these models, indoor climate conditions, energy consumption and product yield are considered. Although these models are developed for special cases it can be valid for other closed greenhouse conditions with some modifications. Another model based on the Simlulink simulation program, GUESS, has been developed by Hill [58]. It is built on three sub-models: one to formulate the indoor climate; and the other two for analyzing the growing plant. Although this model is well defined and it has high level of detail, it is validated only for a tree seedling greenhouse [58].

To assess innovative ideas for temperature and humidity control in the Watergy greenhouse, Bouchholz developed a closed greenhouse model [25]. The Watergy greenhouse is a fully closed greenhouse which is cooled only by natural convection through a cooling tower in the middle of the greenhouse. Therefore, this model, like many other developed models, is valid for a special case and it cannot be generalized for any kind of greenhouse.

Gijzan developed a greenhouse model called INTKAM [19]. INTKAM consists of many sub modules for transmitted radiation into the greenhouse and the crops respectively, photosynthesis phenomena, indoor climate condition and yielding issues. INTKAM is validated for different conditions in a conventional greenhouse but no validation has been done for the closed greenhouse situation [19].

Although there are many developed models that could be used to assess the energy demand of a closed greenhouse, they are validated only for specific conditions. Thus, there are many restrictions in order to employ them under any other conditions. Therefore a general model is needed to be developed in order to assess different closed greenhouse configurations. This model should be validated with experimental data from operating closed greenhouse in order to verify the model.

3. Energy management potential through the closed greenhouse concept

In this paper, the state-of-the art of the closed greenhouse concept has been presented. From this, it is evident that one advantage of closed greenhouse is the potential of reducing the fossil energy consumption in the horticultural industry. Since the

Table 6
Overview of different theoretical energy models.

Type	*Model 1*	*Model 2*	*Model 3*	*Model 4*	*Model 5*
Reference	[59]	[60]	[61]	[58]	[63]
Merit	Using different layer, easy solution, simplification	Fit for unsteady state condition, simple model but can be extended to more complicated, fit for CFD modeling	System is considered to be integrated with PCM TES, Transient energy equations	General and complete model, lumped method is used, agricultural aspects are considered, well adaptive with any CFD programs	Well defined, complete model, adopted to any equation solver programs, heat exchanger parameters are considered
Weakness	Segregated equations, unstability in CFD solution, fit for steady state condition	Tough estimation (refer to specific consideration)	High level of complexity, dependent on greenhouse geometry, tough assumption (refer to specific consideration)	High level of complexity and need some simplifications to be of more friendly use, some empirical equations are used, should be modified for commercial greenhouse	Number of assumptions, need to be modified if other type of indoor climate control will be used, many parameters are given by experimental values
Specific consideration	Uniformity	Uniformity, no leakage, pure water conservation	Uniformity, effect of the humidity and latent heat of the water vapor was ignored, empty greenhouse	Nothing special is ignored, using many empirical equations which need to be validated.	It is validated for the specific case but there is no general validation for this model

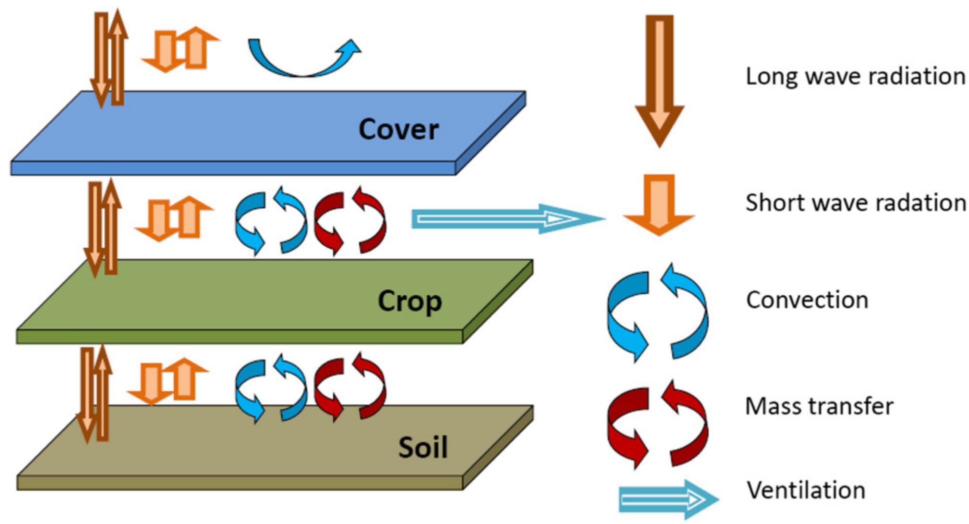

Fig. 4. A schematic of different layers in the greenhouse energy model based on the Levit & Gaspar [59].

Table 7
Comparison between some of developed computer model for closed greenhouse.

Model developer	*Simulation tool/ Programming tool*	*Application*	*Main advantage*	*Validation*	*Specific characteristic*
D.H. Willits et al. [71]	Fortran	Greenhouse integrated with Rock bed storage	Energy analysis regarding to kind of energy storage system	YES	One day simulation model
R.J.Fuller [80]	TRNSYS	Unventilated plastic greenhouse	High potential on the parametric study	Yes	Further parameter should be considered in order to be a generalized model
Hollmuller [72]	TRNSYS	Closed greenhouse	Based on Type 56 in TRNSYS lib.	Yes	More emphasized on heat exchangers
J. Hill [58]	Simulink	Tree seedling nursery, conventional greenhouse	Depth consideration, process based model	Yes	Should be modified for closed greenhouse since it is based on empirical equation for conventional greenhouse
Bouchholz et al. [25]	Undeclared	Watergy Greenhouse	Innovation model and concept	Yes	Just applied for Watergy concept
Heuvelink et al. [19]	Undeclared	Commercial greenhouse	Crop yield monitoring due to closed ventilation concept	No	Agricultural aspect is more emphasized
Hoes et al. [22]	TRNSYS	Closed greenhouse	Energy storage is considered	Yes	Developed for specific case study but it can be modified for general use

amount of absorbed solar energy is almost three times the need for a conventional greenhouse, the closed greenhouse can be known as a crop and heat producing system [8]. There is a need, however, to assess these potentials including mapping promising paths towards realizing this potential.

The growers must overcome many problems in order to maximize the production yield. Open ventilation system in conventional greenhouses causes high heat loss due to high infiltration rate. Therefore it leads to high energy consumption, especially in the cold weather condition. About 90% of energy consumption in the open greenhouses is used for heating [17]. With the open greenhouse, limitations occur due to economics associated with energy consumption, and the seasonal climate conditions causing restriction on crop delivery date. To find a solution to the restriction on delivery time due to seasonal climate variations is always interesting for the growers [10]. At the same time, there is a need for a better pesticides control and CO_2 enrichment system, and thus it is called for new concepts such as the closed greenhouse idea presented above. The closed greenhouse concept can be a solution for all these problems in the open greenhouses, although closed greenhouse has many challenges itself [12]:

- The complexity of climate control.
- The choice of an efficient and proper TES system.
- The need for new structures and insulation material.
- The capital investment.
- The use of new methods and unfamiliar for the growers.

The key point in the closed greenhouse concept is the temperature and humidity control. In the open greenhouses, ventilation is used at the “expense” of increased infiltration and heat loss. The idea of storing the excess heat which is formed inside the greenhouse and using it whenever it is required will solve this problem

but it needs to have a more advanced ventilation system integrating an efficient TES system, dehumidifier and heat exchangers. The temperature is controlled by short term and long term storage systems in the closed greenhouse [17]. A buffer water tank can be used for heat storage for a daily basis to eliminate the mismatch in the heating and cooling demands between day and night and also to handle hourly fluctuations in demand. In order to satisfy the annual heating demand a long-term storage system has to be employed. If available at a specific location, an aquifer can be utilized as an efficient seasonal storage. However, an aquifer may not be able to store heat at a high enough temperature so a heat pump is needed. With more heat collected annually than is needed for the greenhouse itself, the system can be utilized as secondary heating system for surrounding buildings or even as pre-heater, re-heater unit in the CHP [7,10,17].

It is expected that the cooling demand will be covered totally by the TES system (e.g. cold aquifer) and only during some hour per day supplementary cooling systems such as sprinkling water over the greenhouse roof, solar radiation shields and high pressure water mist installation should be needed [53]. It must be noted that using supplementary cooling systems such as sprinkling water or using high pressure water mist will increase the humidity in the greenhouse which would then have to be combined with a proper dehumidifier. Sorption dehumidifiers, however, come with a demand for heat to regenerate.

Based on this state-of-the-art assessment, a major technical challenge of the closed greenhouse concept has been identified as the heat exchangers having to operate at as low temperature differences as possible [7]. Fine-wire heat exchanger can be employed for this purpose so that it is possible to transfer large amount of heat with small temperature difference. It gives the possibility for using an efficient heat pump since the heat pump has the main requirement for extracting external energy in the closed greenhouse [42].

The efficient climate control should be integrated with a proper insulation structure to minimize heat loss from the greenhouse and make it possible to have an accurate indoor climate control system. The grower can also control the level of CO_2 precisely in the closed greenhouse, while in open greenhouses around 90% of supplementary CO_2 is lost due to ventilation windows. In the closed concept, CO_2 can be maintained around a level of 1200 ppm[2] as compare to 800 ppm in a conventional greenhouse [4].

The cost benefit should be considered in any project and this project is not an exception. With regards to the TES system, if any underground system will be applied then drilling cost has been stated as the main investment that should be taken in account in order to find a cost effective solution [17]. The new concept means using new technology and it means that the persons who are related to this new technology should be trained in order to learn the new system and how it works. In the greenhouse area, although the base of growing will be the same in the open and closed greenhouse, there are some main differences between them. These differences will be mostly in the climate control systems [17]. In fact, when considering the concept of "energy efficient buildings", the greenhouse has the potential of moving way beyond being a building with a heating and cooling demand, to actually being an energy source if properly integrated with nearby buildings. Due to sustainable development ambitions, many countries such as Netherland require that a large portion of greenhouses are closed or semi closed by 2020 [20].

There are many different scenarios for energy utilization through the closed greenhouse system; however no specific optimal solution has so far been defined. Many parameters such as greenhouse yields, energy price, feasibility of available thermal energy storage system on the specific condition and climate condition are involved in optimization. Moreover, the optimum scenario should consider the lowest greenhouse gas emission, most efficient energy system and most cost effective system. Since all these criteria cannot be satisfied at the same time in most cases, optimization becomes a task of balancing between the criteria. Therefore different optimum scenarios will be defined due to the particular priority for each case [73]. One of the most interesting aspects for commercial greenhouse optimization is to, through the closed greenhouse concept; obtain a high yield and a high crop quality. However, this often comes at the price of high investment cost. Here, the benefit of scale, for large greenhouses, could be helpful.

Fig. 5 presents a chart of different greenhouse energy management scenarios based on a procedure presented by Van't Ooster et al. [11]. This figure includes available technology which can be implemented in the closed greenhouse concept. Van't Ooster suggested an optimum scenario represented by the Blue line in Fig. 5. Also another scenario has been identified (Red line) based on the state-of-the-art assessment, cf. Table 1. The main differences between the "blue line" scenario and the "red line" scenario are with regards to the energy source, as well as the cooling and dehumidification strategies. Biomass has been recommended by the "blue line" scenario as the energy source for the system while in the "red line" scenario, the solar has been suggested as an alternative beside the biomass as the energy source. The solar collector can be utilized in the closed greenhouse concept in the form of solar shielding in order to maximize the solar energy utilization while at the same time function as a cooling strategy, e.g. like in the previously discussed "Sun Wind greenhouse" [27]. Solar energy can also be used in the form of photovoltaic cells in order to supply a part of electricity demand of the electric devices e.g. heat pump or artificial lighting system. The "blue line" scenario has suggested to utilize only the ground source heat pump system in order to supply cooling in the closed greenhouse while the "red line" scenario proposed two other alternatives, beside the ground source heat pump system, for the cooling method which are shielding with solar panel (or PV) and the night sky radiation. Lower electrical demand and higher energy conservation is expected while applying cooling methods suggested through the "red line". Dehumidification in the "blue line" scenario has been covered only by applying the ventilation with recovery system which is the semi-closed concept. However the "red line" scenario has been suggested to use semi closed concept but also it recommend integrating the system with active cooling using the already installed heat pump. Active cooling using heat pump can be utilized for dehumidification through the fully closed and partly closed concept while the ventilation method is just possible for the semi-closed concept. Both scenarios, the "blue line" and the "red line", have to be analyzed with regards to the energy, economical and environmental performance using formal optimization tools. The cost effectiveness of the closed greenhouse concept is highly dependent on the yield production rate rather than fuel consumption. For example 10% increase in production rate has much more effect on the cost benefits than 10% decrease in fuel consumption [19]. Therefore, the defined scenario should lead to increasing the yield production that is achievable by well-designed indoor climate control system and desirable CO_2 concentration. Further research is thus required to define an economic as well as energy efficient energy management configuration with regards to the closed greenhouse concept.

It should be noted that this study has been primarily concerned with energy analysis through the greenhouse but it does not mean that the plants are ignored in this assessment. Almost all the models which are surveyed are concerned with agricultural issues such as growth rate and yield quality but some assumed an empty greenhouse. The evapotranspiration cannot

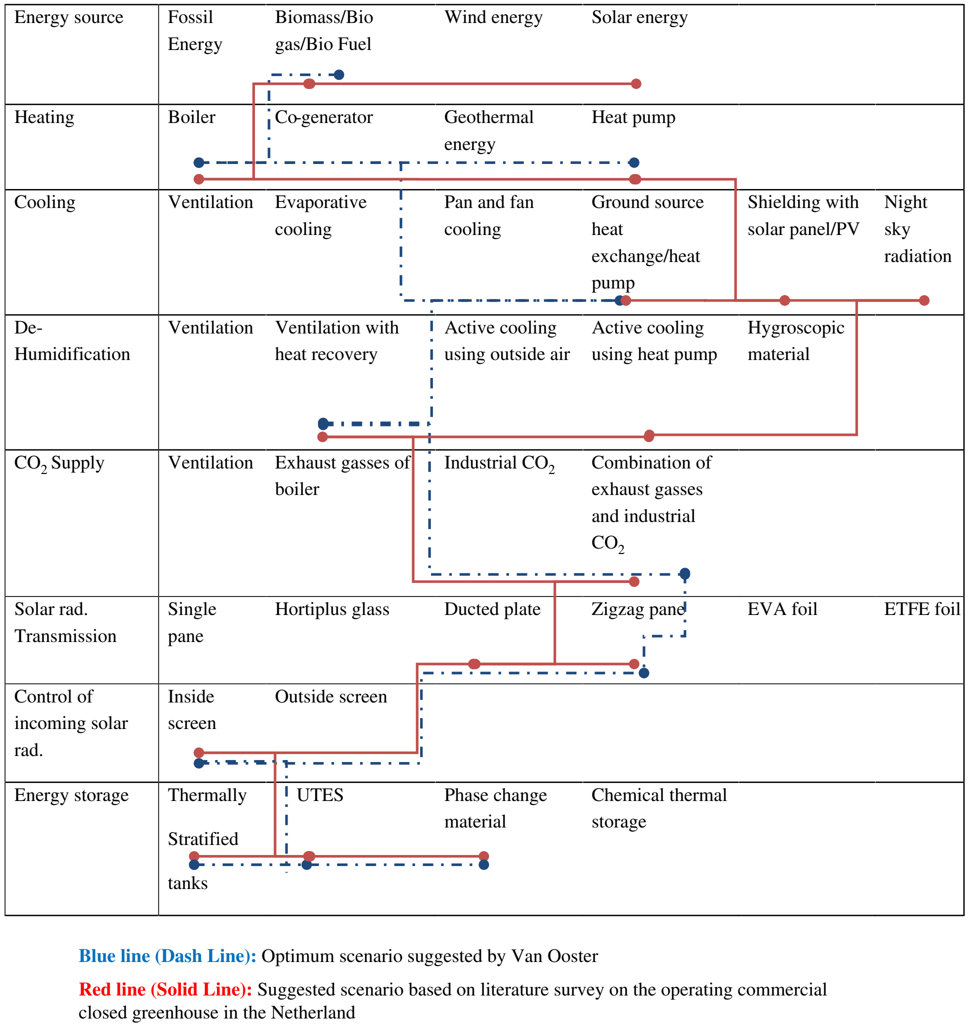

Fig. 5. Morphological chart of different optional technology used in closed greenhouse concept. Blue line: optimum scenario suggested by Van Ooster [11]. Red line: suggested scenario based on lessoned from literature survey on the operating commercial closed greenhouses which are listed in Table 1 [19,20,22,26,74–76]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to be ignored at all since it not only affects the energy balance but also has important role in water conservation [22]. Water conservation is another issue which is promised by closed greenhouse concept. The average water demand for irrigation in the closed greenhouse is about 1.5 l/m^2 per day where around 75% of this amount can be recycled through the system [26].

As mentioned before, since the heat gain in a closed greenhouse is more than enough to satisfy its own heating demand, a combination of open and closed greenhouse sections (partly closed greenhouse) can be a more economic strategy. But the portion of closed greenhouse should be designed precisely in order to cover exactly the energy demand of the rest conventional greenhouse section [13–74]. However, if the increase in yield is high this may make it advantageous to close as much as possible. Fig. 6 presents different opportunities in the thermal energy management systems which can be utilized in the closed greenhouse concept. In this graph different thermal energy sources has been nominated for the base and peak load, to handle the heating as well as the cooling demand. Clearly, there is a need for sizing and design to consider fraction of the greenhouse to be closed, the auxiliary peak capacity along with the size of seasonal and daily TES, as well as the technical options for harvesting excess heat, storage, humidity control and auxiliary cooling/heating. Aside from "energy savings", the potential of saving water, decrease the use of pesticides with the opportunity of "organic labeling", as well as the increased yield must be included in the overall analysis of cost-effectiveness. Thus, it appears that the closed greenhouse present a worthy multi-discplinary design challenge which, if realized, have the opportunity to address many aspects of the concept of true sustainability.

4. Concluding remarks

In line with world-wide sustainable development policies, the closed greenhouse concept was introduced 1997. The main aim of this innovative idea was to increase the production yield rate and achieve energy conservation, along with improved indoor climate control for horticultural greenhouses. This paper has assessed the state-of-the-art of this concept with regards to improving energy management in a greenhouse.

Heat loss through the closed greenhouse is designed to be minimum in comparison with the conventional greenhouses since there are no open ventilation windows. Therefore the excess solar energy which is passing through the greenhouse can be harvested and stored in the thermal energy storage system for utilization at a later time. Temperature and humidity control are identified as the two main challenges in the closed greenhouse concept. Although many studies have been done with regards to

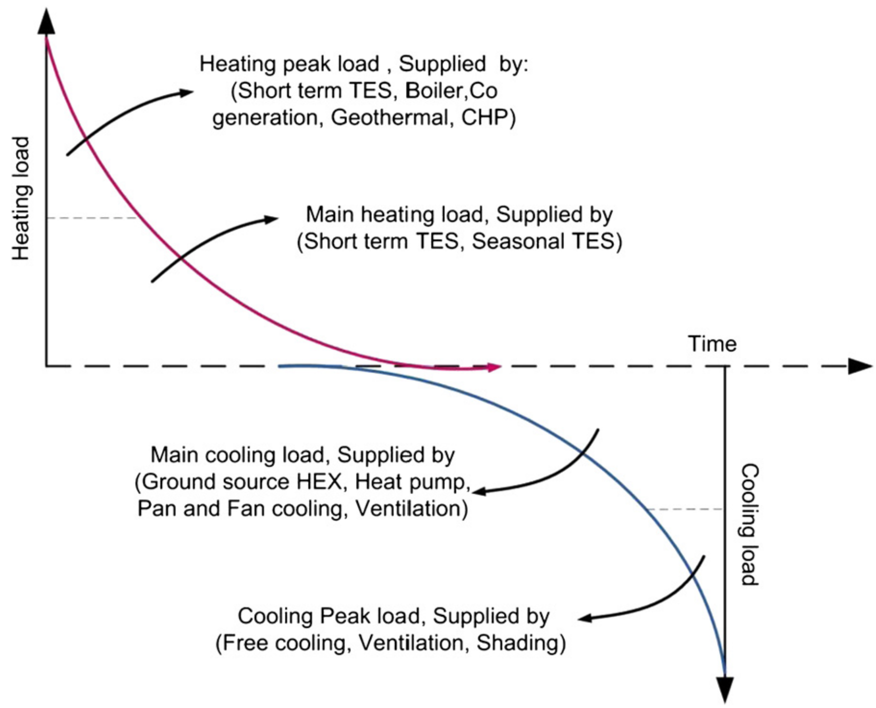

Fig. 6. Thermal management for the closed greenhouse.

heating and cooling systems in the greenhouse, more is needed on the efficient heating and cooling system adapted to the closed greenhouse concept. The present investigation has found that in principle, a closed greenhouse can supply almost three times more than its annual heating demand.

From a cost-effectiveness point of view, the closed greenhouse may not be effective if only energy price is considered in the analysis since the current price of fossil fuel such as natural gas is relatively low. However it has the potential to be economical when other parameters such as total energy efficiency, production yields rate and CO_2 control has been added to the economical analysis as well. For example, this study highlights information that the increased yield affects the cost efficiency more than the decrease in the fuel consumption. Since the growing condition in the closed greenhouse can be well controlled they can operate everywhere. Thus, it is here predicted that they will be the next generation of the horticultural greenhouse needed for a sustainable future.

Although there are many innovative studies regarding the closed greenhouse concept, a number of interesting points remain to be investigated. For example, since the closed greenhouse concept is highly dependent on the thermal energy storage, its progress is closely linked to TES technology development. There is different thermal storage systems that can be utilized in this idea and that should be designed based on energy management system for each single specific greenhouse. The daily, monthly, seasonal and annual energy analysis can be used in order to have better understanding on the energy flow in the system and to optimize it. Feasible assessment in integrating other available energy technology such as solar and other types of renewable technology could be other option for future study. Thus, there are many energy management strategies for the closed greenhouse that should be considered in order to find optimized solutions for various cases. Then, the closed greenhouse has the potential to be an important key for sustainable societies of the future, providing reliable plant growing with low environmental impact and in addition providing heat to a local community in its vicinity.

Acknowledgment

The authors would like to greatly acknowledge the "Swedish Farmer's Foundation for Agricultural Research" and "Slottsträdgården Ulriksdal" Greenhouse for their financial supported in this project and special acknowledge the Energy department colleagues who help authors in peer reviewing of this paper.

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